Application Note

Comparing Active vs. Passive High-Speed/RF A/D Converter Front Ends

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ABSTRACT

Designing the analog input interface for a high-speed converter can be a daunting task throughout the product design process. Even though 10Gsps high-speed converters can deliver as much as 10GHz of bandwidth, most of the limitations involve a front-end design.

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1 Introduction

As both amplifier and balun specifications catch up in bandwidth and performance, note the importance to understand some of the nuances involved when interfacing with the front-end. This article includes some of the most significant considerations and trade-offs when designing a high-speed, wide-band converter, for example, +6GHz, front-end.

2 Active (Amplifier) vs. Passive (Transformer/Balun) Tradeoffs

Amplifiers are active, provide gain, have inherent noise, need a power supply and decoupling, and consume power. A balun, however, does not add noise nor consume power. These are just fundamental differences; this is too early to decide which is best to choose just yet. What is important, is understanding the trade-offs set by the application (Figure 2-1).

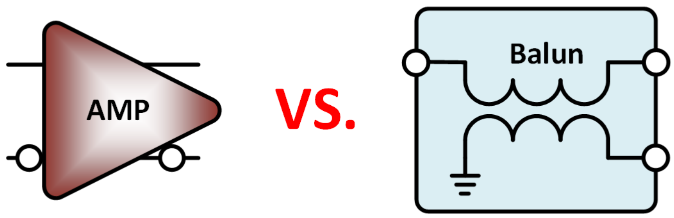

Figure 2-1. RF Converter Front-End Choices: Amplifiers = Active vs. Baluns = Passive

3 Amplifiers vs. Baluns: The Advantages

On the active side, you can use an amplifier to preserve the DC levels, also known as the DC bin. This type of amplifier/ADC interface in the signal chain is often referred to as DC coupling. Therefore, these DC levels hold some important information in a particular application.

Amplifiers can also maintain better isolation in previous stages in the RF signal-chain lineup, which matters when using unbuffered converters, or if standing waves are evident when the front-end *match* is not quite right within the frequency band relevant to the application.

Although amplifiers inherently provide +6dB of gain or more, that gain is independent of the output impedance. The amplifier's bandwidth do not suffer or drop when this comes to subtle fluctuations in impedance across the frequency band of interest. Because the amplifier is more autonomous with gain vs. output impedance, amplifiers typically enjoy a more *ripple-free* passband.

On the passive side, baluns cannot pass DC levels, and transformers are inherently flux coupled devices, which make them good AC couplers. Or, DC blockers. For inherently AC-coupled RF signal-chain lineups, baluns are a great choice. Baluns are naturally passive and need no power supply nor supporting circuitry such as decoupling capacitors or ferrite beads for power. And because baluns need no power supply, baluns are essentially noiseless.

Surface mount technology (SMT) baluns is common in providing upwards of 10GHz and even 20GHz of bandwidth. If you opt for a modular type balun—for use in a lab setting or high-end instrumentation—those baluns are hitting upward of 80GHz at the time of this writing. If the bandwidth requirement for the application is paramount and you need more than 5GHz, the balun seems to outshine the amplifier.

4 Amplifiers vs. Baluns: The Disadvantages

A balun is more like a window than a door, and provides little to no isolation. Therefore, RF signal-chain lineups sometimes need to include isolation from the balun's passing standing waves, impedance mismatches and *kickback*. Kickback is a common term used to describe the existence of charge injection from the opening and closing of the converter's internal sampling switch capacitor if the ADC is unbuffered.

Unlike amplifiers, passive baluns can be lossy; and a high-frequency balun needs a wide-band matching pad (3 to 6dB) to help *stiffen* the broadband impedance across multi-gigahertz bands. What this means is that the balun is more gain-dependent of the output impedance, unlike an amplifier. Therefore, adding a matching or attenuation pad adds more loss into the RF signal-chain lineup and can increase the overall noise figure of an analog receiver design but provide increased BW. Finally, because of the broadband match approach, standing waves add and subtract from the passband flatness, causing ripple throughout the passband. See *The 3rd dB: Why a Lossy Attenuation Network Pad Works Well With RF ADCs*, application brief for more information on matching pads with baluns.

Also, as an amplifier is inherently active, the amplifier also inherently outputs noise and spurious distortion as well. The noise can vary depending on the amplifier's design, but all amplifiers can have some amount of noise and spurious output, which ultimately the ADC can see. For example, if a particular amplifier has a gain of 12dB, an output-referred noise of 5nV/√Hz and a 12bit, 10Gsps ADC with an 8GHz input bandwidth, 1Vpp differential full scale has a signal-to-noise ratio (SNR) of roughly 60dB. These two devices can effectively *add* together and therefore, worsen the ADC's noise floor and a lower the dynamic range, in this case worsening SNR by 5.45dB or...

$$SNR_{total} = 20 \times \log\left(\frac{\frac{\frac{1}{2}}{\sqrt{2}}}{\sqrt{NoiseADC^2 + NoiseAMP^2}}\right) = 54.5 \quad dB \tag{1}$$

Where,

$$NoiseADC = \left(\frac{\frac{\frac{1}{2}}{\sqrt{2}}}{10^{\left(\frac{60}{20}\right)}}\right) = 354uVrms \tag{2}$$

and

$$NoiseAMP = 5nV \times \sqrt{1.57 \times 8000M} = 560.4uVrms \tag{3}$$

Amplifiers not only have noise, but are prone to linearity as well. This linearity effectively adds to the ADC's linearity, making this worse overall. For example, if an amplifier's worst spurious output is –80dB and the ADC's worst spurious is also –80dB, the best effective linearity in an amplifier-plus-ADC interface design at this particular frequency is –77dB or...

$$Spurious = 20 \times \log\left(\sqrt{\left(10^{\left(\frac{-80}{20}\right)}\right)^2 + \left(10^{\left(\frac{-80}{20}\right)}\right)^2}\right) = -77dB \tag{4}$$

To combat against any noise or spurious output in the band of interest, an anti-aliasing filter (AAF) between the two devices can help. How much this can help depends on how narrow or broad the filter design is and on the AAF's roll-off criteria. Extra supportive components also need to be added to support this interface between the amplifier and ADC interface. Please see *How anti-aliasing filter design techniques improve active RF converter front ends* on how to properly design AAFs between amplifiers and ADCs.

5 Understanding the Importance of Phase Imbalance

If the application frequency plan includes even order distortion—the second (HD2), fourth (HD4), sixth harmonics (HD6), and so on—then you must also look at phase imbalance when designing the analog front-end interface. Both amplifiers and baluns have a finite amount of phase imbalance between the output signals, which typically gets worse (deviates) across higher and higher frequencies.

Phase imbalance is the term used to quantify the amount of phase imbalance between two differential signals. Since the ADC's analog inputs are typically a differential interface, the two inputs need to be equal in amplitude and 180 degrees out of phase. For example, if Ain+ = –2 degrees and Ain– = 185 degrees, that produces a 7 degree shift, which translates into the frequency domain or fast Fourier transform (FFT) plot as a worse even-order distortion; that is, the second harmonic gets worse.

Unfortunately, there is really no real way to quantify how much phase imbalance your signal chain can take before starting to degrade system performance. This is because every component with a differential input or output interface, active or passive, can have some inherent finite amount of phase mismatch at some frequency. There is really no way to designed for balance an IC internally, a balun's windings, or even multiple cables to the absolute designed for phase.

When performing balanced or differential test measurements in the lab, where you plan to use cables or adapters in the test setup, these *extras* need to phase-matched as well.

If there is still doubt, and you like a bit of math, please see Appendix A for a full phase imbalance derivation using an ADC model. Here, the ADC model uses a third-order transfer function and a pair of sinusoid signals to prove how phase imbalance gives rise to even-order distortion as shown in Figure 5-1.

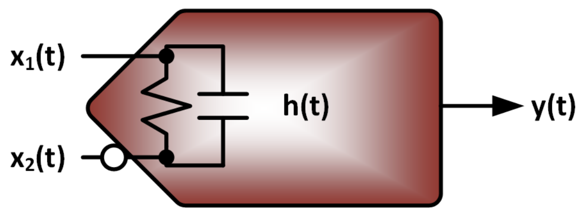

Figure 5-1. Differential Input Signaling Mathematical Model

Where each input signal is represented as:

$$\begin{aligned} x_1(t) &= k_1 \times \sin(\omega t) \\ x_2(t) &= k_2 \times \sin(\omega t - 180° + \theta) = -k_2 \times \sin(\omega t + \theta) \end{aligned} \tag{5}$$

The ADC is a modeled as a third-order expression:

$$h(x(t)) = a_0 + a_1 x(t) + a_2 x^2(t) + a_3 x^3(t) \tag{6}$$

The output is the convolved expression of the two:

$$y(t) = (2a_1 k) \times \sin(\omega t) + \left(2a_3 k^3\right) \times \sin^3(\omega t) \tag{7}$$

6 Phase Balance with Amplifiers and Baluns

Returning back to the topic of amplifier and balun trade-offs, baluns come in many forms, packages and designs. Classic ferris-type baluns are usually prone to phase imbalance, the recommendation is to consult the data sheet before making your final selection and not base your selection only on insertion loss or the bandwidth that the balun can cover for your particular application. Smaller packages that use lithography structures have tighter tolerances and better repeatability, which typically means there is a possibility to improve the phase imbalance. However, this comes at the cost of smaller or more narrow bandwidth choices, which is not always good if the design calls for lower frequencies in the UHF bands near DC.

Module baluns produce some of the best phase imbalance results, but they are big, bulky, and costly—as much as $2,500 for just one modular balun. These really expensive baluns provide some of the widest bandwidth-hitting DC frequencies on the low BW-end and maintain good phase flatness into the multi-gigahertz regions. Figure 6-1 compares the phase imbalance of some types of baluns available on the market today.

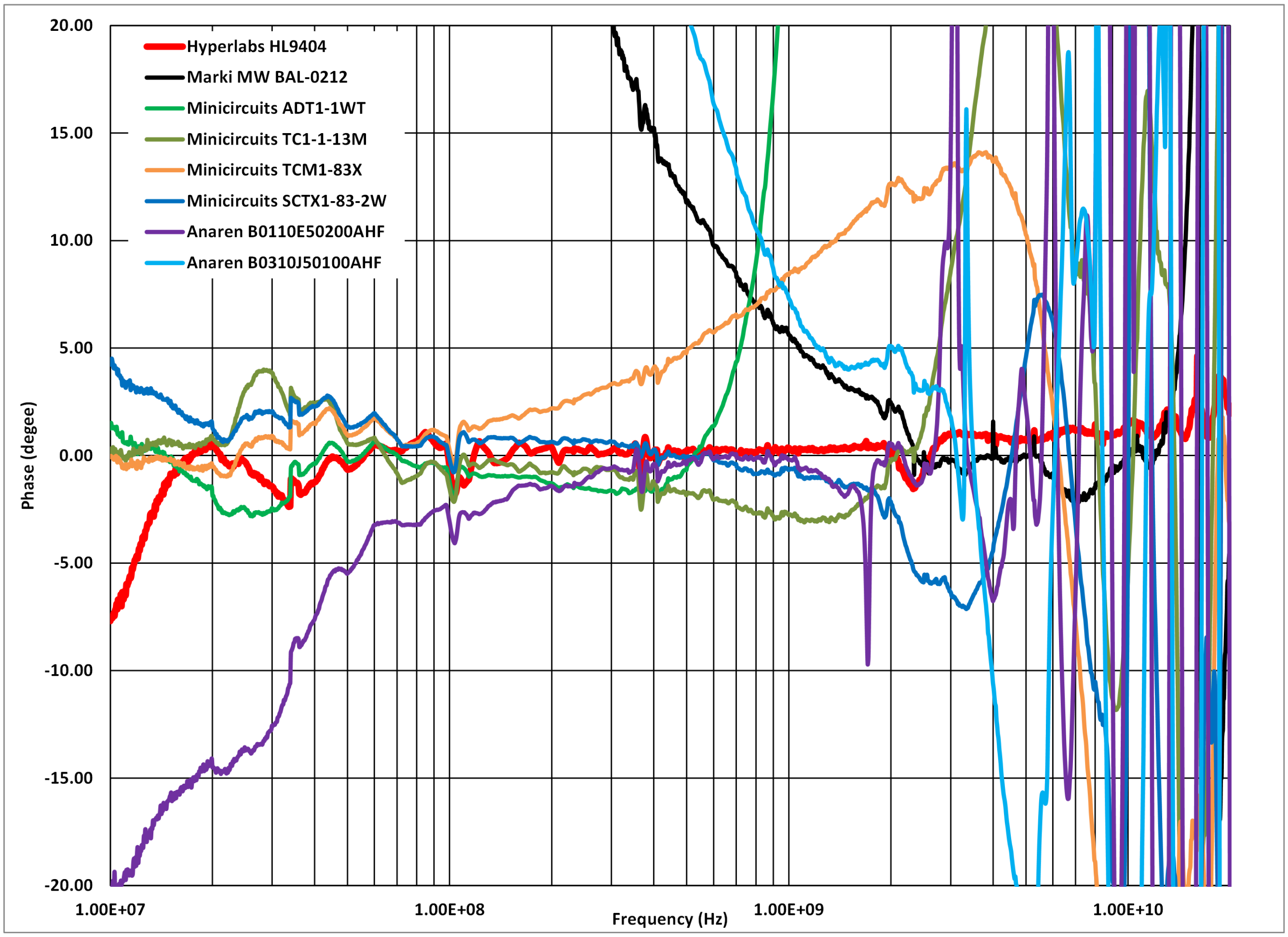

Figure 6-1. Comparison of Balun Phase Imbalance

If your design calls for a wide bandwidth but there are also cost constraints, one neat trick is to put two baluns or transformers back-to-back to improve the phase imbalance. See Figure 6-2 and Figure 6-3. The only downside is the doubled amount of PCB area to implement this type of front-end structure.

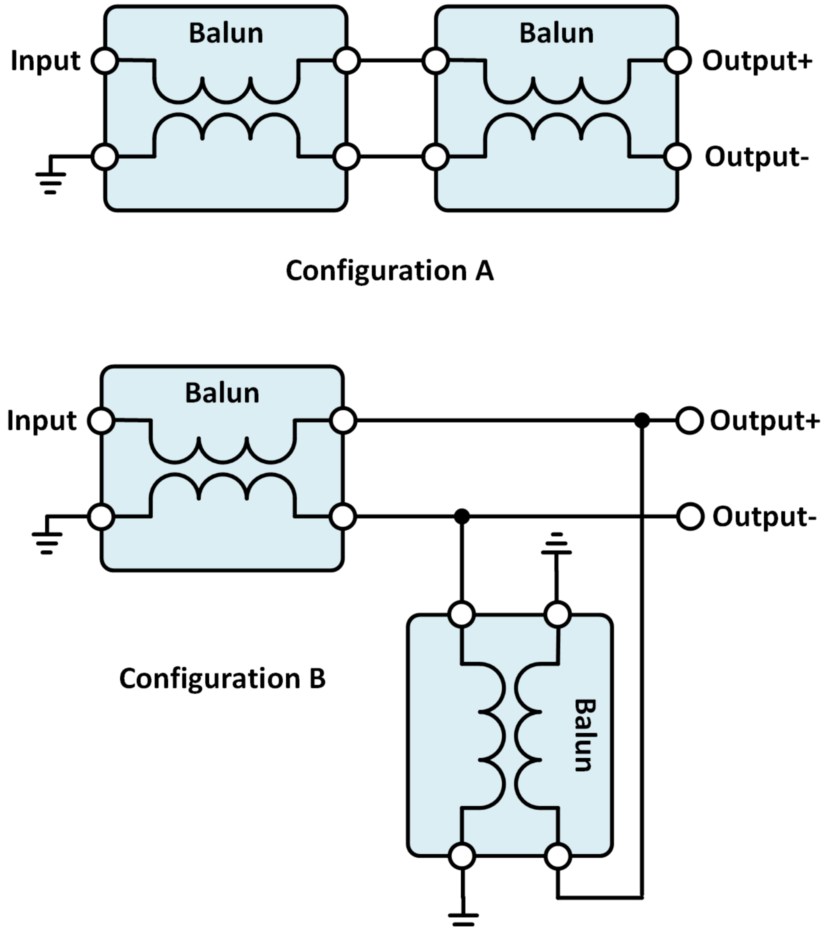

Figure 6-2. Various Double-Balun Configurations Can Improve Phase Imbalance

Using either balun configuration A or balun configuration B from Figure 6-2, or the red and blue curves in Figure 6-3, you can see that a phase imbalance of 5 degrees or less can be extended out to 3GHz over the original single-balun configuration, over the green curve. If using one of these balun configurations, note that each balun combo can have varying degrees of improvement.

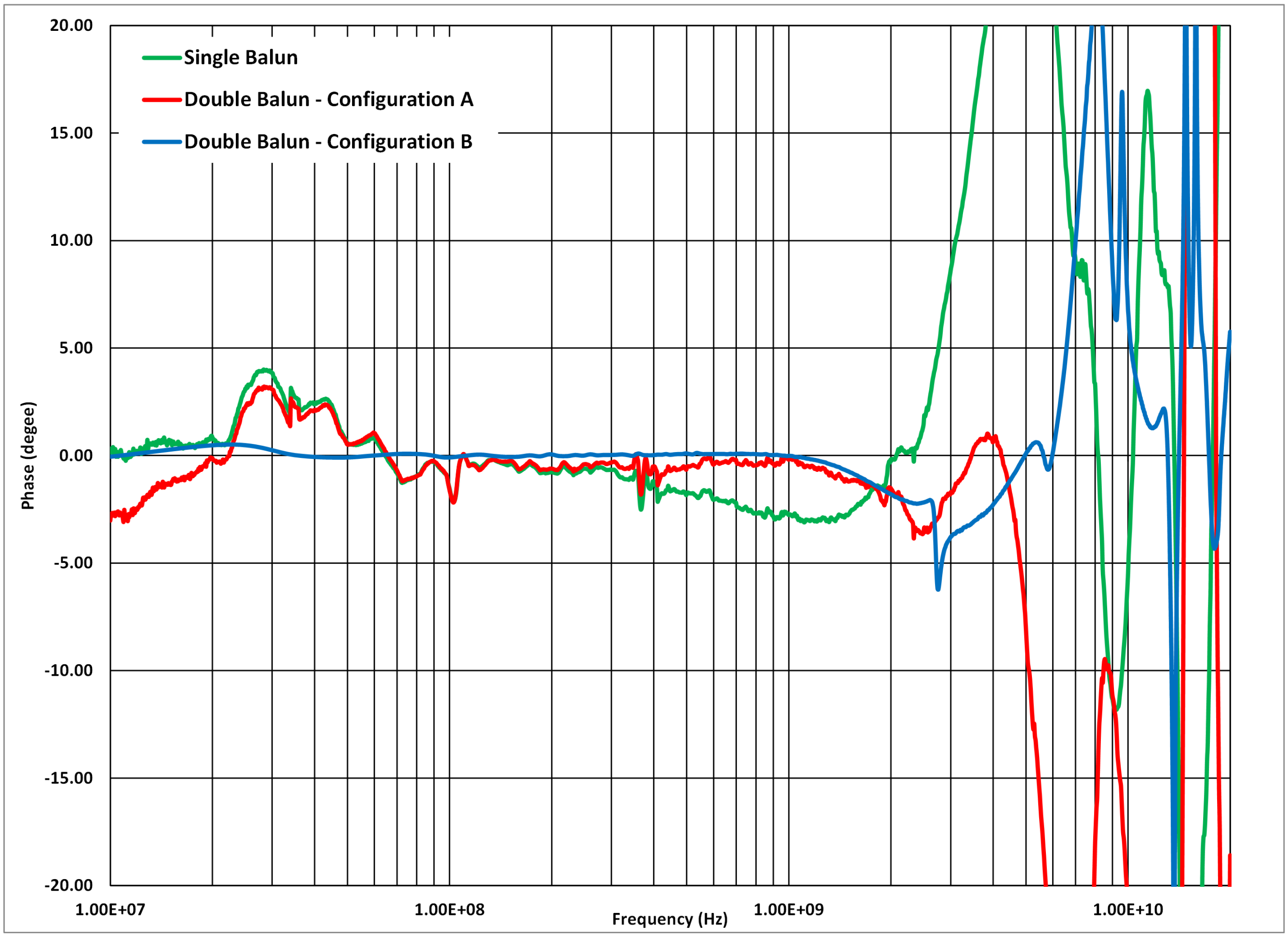

Figure 6-3. Comparison of Single-Balun vs. Double-Balun Phase Imbalance Improvement

Phase balance is also prevalent on the amplifier side. Because low-noise amplifiers and gain blocks have single-ended inputs and outputs, you can assume that these types of amplifiers do not have good phase imbalance and have high even-order distortion, which is why HD2 is not specified in these types of amplifier data sheets.

Fully differential amplifiers (FDAs) are the classic amplifier input interface to the ADC with differential inputs and outputs. Even though the FDA enables single-ended signal to a differential signal conversion, tying one input pin to ground in some fashion, the FDA inputs are sensitive to this reference shift, and therefore, the FDA can exhibit more even-order distortion in this configuration.

FDAs are typically characterized with wide-band modular baluns to capture the published performance metrics. However, the TRF1208 amplifier uses a compensated input structure, allowing for a single-ended input interface by default and removing the dependency of the balun on the inputs like a traditional FDA. TRF1208 input structure fits well when interfacing to RF analog receiver cards, which are classically single-ended.

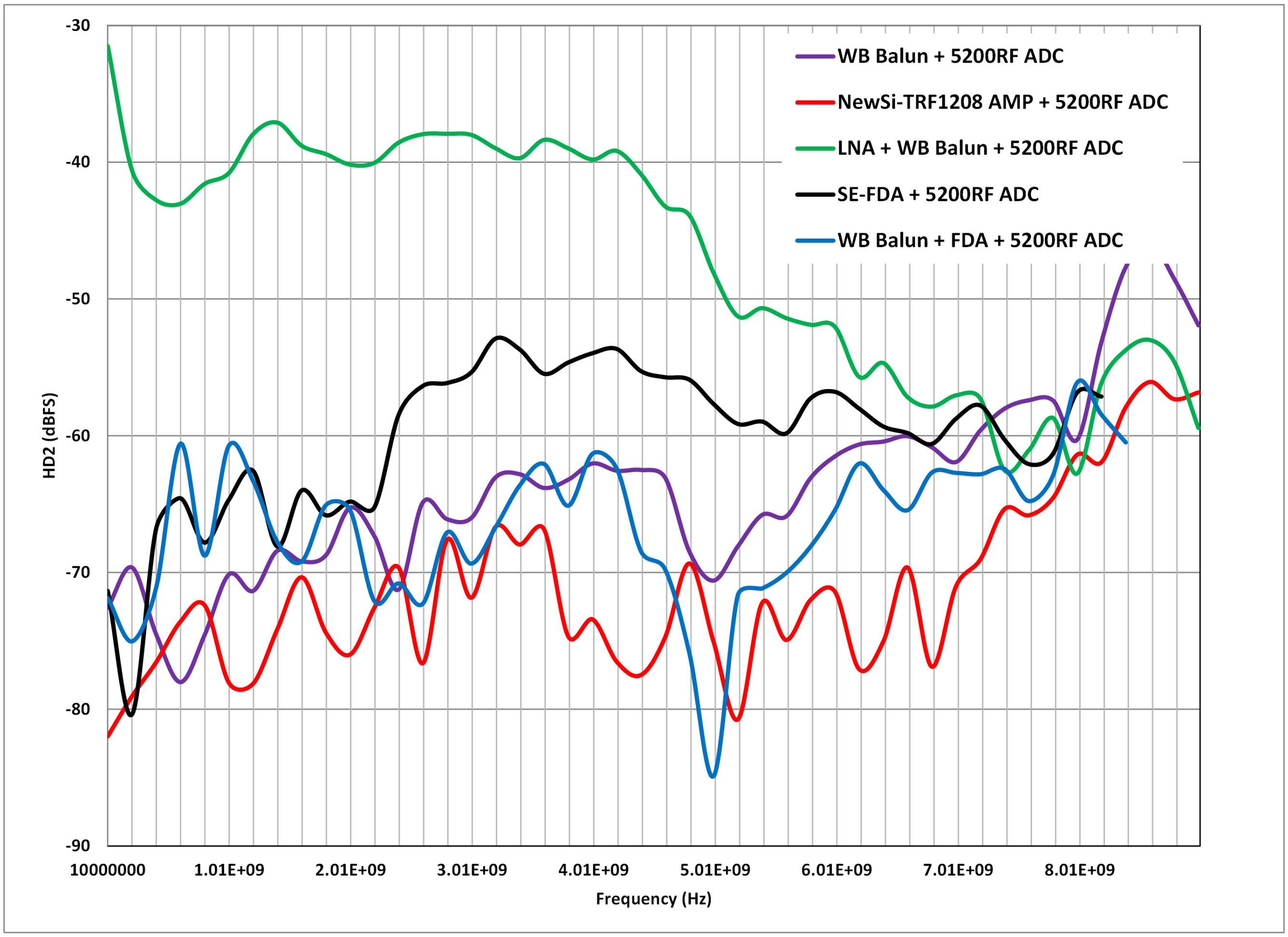

Figure 6-4. Even-Order Distortion, HD2, Comparison vs. Analog Input Frequencies up to 10GH

Using the ADC12DJ5200RF ADC, Figure 6-4, directly compares a typical wide-band balun interface, the TRF1208 interface, a low-noise amplifier plus wideband-balun interface, and an FDA with and without a balun on the differential inputs.

Notice that in all of these configurations below 1GHz, the performance is fairly equal. As the analog input frequency climbs past 2GHz, however, there is a distinct growth in the even order distortion for all combinations except the TRF1208 (red curve).

7 Summary

Both active and passive front ends have pluses and minuses. Before making a choice in haste, please understand the application, which can help determine which front end design path to follow: an amplifier or balun. Once decided between active or passive interface, look at the individual trade-offs related to phase imbalance sensitives, gain, power and input power required to achieve full scale of the ADC. Collecting this information in a spreadsheet can help you quickly determine which device is best for your next +5GHz design.

8 References

- Texas Instruments, *The 3rd dB: Why a Lossy Attenuation Network Pad Works Well With RF ADCs*, application note.
- Texas Instruments, *How anti-aliasing filter design techniques improve active RF converter front ends*, analog design journal.

A Appendix A

Magnitude and Phase Imbalance Derivation

Mathematical model of two input signals to represent the differential interface into the ADC:

$$x_1(t) = (k_1)\sin(\omega t)$$
$$x_2(t) = (k_2)\sin(\omega t - 180° + \rho) = -k_2\sin(\omega t + \rho) \quad (8)$$

Mathematical model of the ADC, as a symmetrical third-order transfer function:

$$h(x(t)) = a_0 + a_1\, x(t) + a_2 x^2(t) + a_3 x^3(t) \quad (9)$$

Putting the two together, this can be represented as follows:

$$y(t) = h(x_1(t)) - h(x_2(t))$$
$$y(t) = a_1[x_1(t) - x_2(t)] + a_2\left[{x_1}^2(t) - {x_2}^2(t)\right] + a_3\left[{x_1}^3(t) - {x_2}^3(t)\right] \quad (10)$$

In the case, where there is no imbalance to the two input signals, the transfer function of the ADC is modeled as follows, where magnitude is $k_1 = k_2 = k$ and phase is exactly 180° out of phase (φ = 0°):

$$x_1(t) = (k)\sin(\omega t)$$
$$x_2(t) = (-k)\sin(\omega t)$$
$$y(t) = (2a_1 k)\sin(\omega t) + \left(2a_3 k^3\right)\sin^3(\omega t) \quad (11)$$

With simplification of the model, this can be seen that the even harmonics cancel and the odd harmonics do not or:

$$y(t) = 2\left(a_1 k + \frac{3a_3 k^3}{4}\right)\sin(\omega t) - \left(\frac{a_3 k^3}{2}\right)\sin(3\omega t) \quad (12)$$

Looking at the case where the magnitude is imbalanced, where $k_1 \mp k_2$ and φ = 0 and phase is balanced. The two inputs signals look as follows:

$$x_1(t) = (k_1)\sin(\omega t)$$
$$x_2(t) = (-k_2)\sin(\omega t) \quad (13)$$

With some substitution, the following can be found:

$$y(t) = \frac{a_2}{2} \times \left({k_1}^2 - {k^2}_2 = {}_2\right) + \left(a_1(k_1 + k_2) + \left(\frac{3a_3}{4}\right) \times \left({k_1}^3 - {k_2}^3\right)\right)\sin(\omega t) -$$
$$\left(\frac{a_2}{2}\right) \times \left({k_1}^2 - {k_2}^2\right)\cos(2\omega t) - \left(\frac{a_3}{4}\right) \times \left({k_1}^3 - {k_2}^3\right)\sin(3\omega t) \quad (14)$$

As shown from the equation that the second harmonic is proportional to the difference of the squares of the magnitude terms, or:

Second harmonic is α $k_1{}^2$ - $k_2{}^2$

Looking at the case where the phase is imbalanced, where $k_1 = k_2$ and φ ∓ 0 and the magnitude is balanced. The two inputs signals look as follows:

$$x_1(t) = (k_1)\sin(\omega t)$$
$$x_2(t) = (-k_1)\sin(\omega t + \rho) \quad (15)$$

With some substitution, the following can be found:

$$y(t) = \left(a_1 k_1 + \frac{3a_3 {k_1}^3}{4}\right) \times (\sin(\omega t) + \sin(\omega t) \times \cos(\rho) + \cos(\omega t) \times \sin(\rho))$$
$$- \left(\frac{a_2 {k_1}^2}{2}\right) \times (\cos(2\omega t) - \cos(2\omega t) \times \cos(2\rho) + \sin(2\omega t) \times \sin(2\rho))$$
$$- \left(\frac{a_3 {k_1}^3}{4}\right) \times (\sin(3\omega t) + \sin(3\omega t) \times \cos(3\rho) + \cos(3\omega t) \times \sin(3\rho)) \quad (16)$$

As shown from the equation that the second harmonic is proportional to the square of the magnitude term, or:

Second harmonic is α $k_1{}^2$

In summary, the second harmonic is influenced by the phase imbalance more so than the magnitude imbalance. Therefore, the phase imbalance and second harmonic is proportional to the square of k_1. While for magnitude imbalance, the second harmonic is proportional to the difference of squares of k_1 and k_2. Since k_1 and k_2 are typically and approximately equal, the difference of $k_1{}^2$ and $k_2{}^2$ is small. Thus, the second harmonic is generally not affected as much do to magnitude imbalance.

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